# REFLEX TRIODE X-RAY SOURCE RESEARCH ON GAMBLE II [*]

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## Abstract

Reflex diode and triode x-ray sources are investigated on Gamble II (2 MV, 2 Ω, 100 ns) to understand the coupling of high-power (TW), MeV-electron beams to thin converters in order to optimize emission of sub-100-keV x-rays. Thin converters reduce self-absorption of low-energy x-rays, but the beam electrons must pass many times through the converter for efficient x-ray production. The triode configuration was found to be superior to diode configurations for this purpose. A large range of converter thicknesses were tested, from 2.5-μm gold to 250-μm tantalum. The highest dose was obtained from 25-μm tantalum, although the spectrum became softer for thinner converters. Computer modeling is in very good agreement with the experimental data, and indicates that electron loss to large radius determines the optimum converter thickness. The coupling efficiency for thinner converters could be improved by decreasing the triode impedance, a motivation for developing similar diodes on higher-current generators.

## I. REFLEX DIODE/TRIODE SETUP

The reflex diode/triode configuration on Gamble II is shown in Fig. 1. The Gamble II pulse (+2 MV, 1 MA, 100 ns) is delivered via a water-filled coaxial transmission line from the left in the figure. The center conductor is terminated in vacuum by an aluminum plate that has twelve holes for a post-hole convolute, indicated in red in Fig. 1. This electrode is pulsed to positive high voltage. The x-ray converter is stretched taut in the center of the post-hole plate. The vacuum chamber is grounded. Two cathodes are arranged to inject electrons toward the converter from both sides. Each cathode consists of twelve stainless steel, 1-cm-diameter tubes in a circular array to approximate a continuous cylinder. The plates connecting to the tubes have radial slots between each pair of tubes to provide inductive isolation and prevent azimuthal currents. The (aluminum) cathode plate inside the center conductor is connected to ground through twelve posts. This cathode assembly is referred to as the upstream cathode, indicated in blue in Fig. 1. This

cathode injects electrons to the right, the same electron direction as for a conventional x-ray diode in negative polarity, where the cathode is connected to the (negative) center conductor and the converter is connected to the grounded conductor. The second (stainless) cathode, indicated in green in Fig. 1., injects electrons to the left, toward the generator. This cathode is referred to as the downstream cathode. The downstream cathode/anode combination is similar to previous reflex diode experiments performed on Gamble II [1, 2]. Reflex triode x-ray sources have also been investigated extensively at L-3 Communications, Pulsed Sciences Division in San Leandro, CA [3].

Positive polarity operation has several advantages for diodes with reflexing converters. In negative polarity, the converter is grounded. Electrons that pass through the converter are stopped in a low-Z absorber. The vacuum window must be strong enough to contain the debris from the vaporized converter and beam absorber. In positive polarity, no beam absorber is required, reducing the attenuation and the debris impulse on the vacuum window. A reflexing converter can be many times thinner
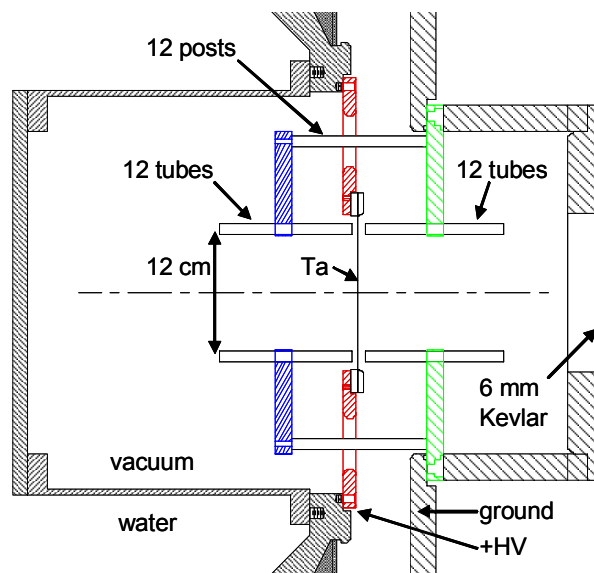


**Figure 1**. Cross section of the reflex diode/triode experiment on Gamble II.

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## Report Documentation Page

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| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **JUN 2007** | **N/A** | **-** |

| 4. TITLE AND SUBTITLE | 5a. CONTRACT NUMBER |
|---|---|
| **Reflex Triode X-Ray Source Research On Gamble** | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |

| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) | 8. PERFORMING ORGANIZATION REPORT NUMBER |
|---|---|
| **Plasma Physics Division, Naval Research Laboratory Washington, DC 20375 USA** | |

| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
|---|---|
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.**

14. ABSTRACT
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15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **SAR** | **6** | |

than a conventional converter in negative polarity, further reducing the debris mass. The vacuum window can then be made more transmissive for low-energy x-rays, in principle. The present work concentrates on optimizing the converter thickness for transmission of low-energy x-rays; optimizing the vacuum window is left for future work.

Electrical diagnostics include voltage monitors near the end of the water line, current monitors in vacuum and at the end of the water line, and current monitors in the cathode structures to measure the current to each cathode. For a few shots, the ion current from the downstream diode was measured using a Rogowski loop, but this diagnostic limited the field of view for radiation measurements and was not used regularly.

Radiation diagnostics are located outside the vacuum chamber near the axis at various distances. A pinhole camera located 1 meter from the converter imaged the time-integrated x-ray emission. A scintillator-photodiode at 1 meter measured the time-dependent x-ray emission. An image plate located 6.7 meters from the source recorded the transmission through an aluminum step wedge, to diagnose changes in the soft part of the transmitted x-ray spectrum. The x-ray dose was measured using $CaF_2$ thermoluminescent dosimeters (TLDs) located at the vacuum window (18-27 cm from the converter), near the pinhole camera and near the image plate.

## II. EXPERIMENTAL RESULTS

Experiments were performed using the upstream and downstream diodes individually, and together in the triode

configuration. In general, the triode configuration was superior in several respects as described in more detail below.

### A. *Diode experiments*

The downstream diode is similar to previous reflex diodes tested on Gamble II.[1, 2] Electrons emitted from the cathode can pass through the converter into the vacuum space inside the center conductor. Electron space-charge can accumulate there, forming a virtual cathode that reflects subsequent electrons back toward the converter. This mechanism allows much greater interaction of the electron beam with a thin converter than would be the case if the beam were stopped in an absorber, or lost to the center conductor walls after its first pass through the converter.

Downstream diode experiments used 6-mm anode-cathode (AK) gaps to match the 2-$\Omega$ impedance of Gamble II. The peak voltage for all cases were in the 1.3-1.6 MV range. The tantalum converter thicknesses were 15, 25 and 250 $\mu$m. (The CSDA range for 1.5 MeV electrons in tantalum is 700 $\mu$m.) Most of the bremsstrahlung production occurs in a converter thickness of approximately 1/3 of a CSDA range; thicker converters only add attenuating material that reduces the x-ray transmission out of the converter. All cases coupled 52-60 kJ of electrical energy to the diode.

The x-ray dose is a measure of the efficiency of the beam coupling to the converter. [All dose values quoted in this paper have units of rads($CaF_2$) at 1m.] For the 250-$\mu$m converter, the dose was 150 rads. For the 25-$\mu$m converter, the dose was 126-145 rads, only a small decrease considering that the converter thickness was a
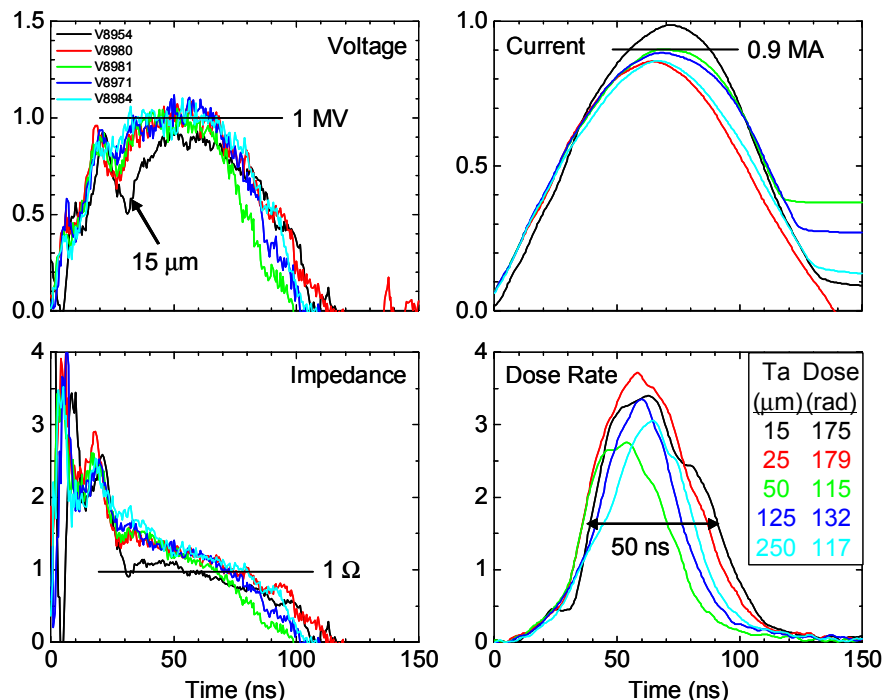


**Figure 2**. Electrical waveforms and dose-rate data for triode shots with different converter thicknesses.

factor of ten less than the optimum value. The dose from the 25-μm converter decreased by a factor of 2.5-3 when a carbon plate was attached to the back side of the converter to absorb the electrons after their first pass through the tantalum, proving (again) that the virtual cathode mechanism causes reflexing through thin converters. The dose from the thinnest converter tested, 15 μm, was 101-105 rads. This converter thickness seems less efficient than the 25-μm thickness, although the reduced thickness will allow lower-energy x-rays to escape.

Dose measurements using the upstream diode were similar to the downstream diode; 50-μm converters produced 150 rads, 15-μm converters produced 111 rads. This configuration is different from the downstream diode in two respects. The electron beam that passes through the converter sees the cathode potential, while the downstream diode injects its electrons into a cavity at anode potential. The second difference is the post-hole convolute, which appears to work well for this configuration.

### B. Triode experiments

The triode was tested for 52 x-ray shots. Data for triode shots are shown in Fig. 2. These shots were selected as "best shot" examples for a range of tantalum foil thicknesses. The triode appears to operate best with AK gaps similar, or slightly greater than, the AK gaps used for the upstream and downstream diodes, so the impedance was reduced to about 1 Ω and the peak voltage was 0.9-1 MV. The electrical waveforms are similar for the different thicknesses, except for the thinnest tantalum (15 μm) which has a reduced voltage and impedance after the initial voltage rise. This could be related to more reflexing causing increased ion current for this foil thickness. The dose is greatest for the thin foils (15 and 25 μm), and decreases as the foil thickness is increased. The dose and dose rate with 15-μm tantalum are increased with the triode by about 70% compared with the reflex diodes, despite the reduced voltage. This makes the triode better than the diodes for producing sub-100-keV x-rays.

Sample images from the x-ray pinhole camera are shown in Fig. 3 for the diode and triode configurations, all with 15-μm tantalum converters. The circular boundary with radial spokes is the downstream cathode plate (green

in Fig. 1). Twelve bright emission lines begin near the cathode tubes and propagate radially inward, forming a more-or-less concentrated pinch near the center. The triode example shows a more diffuse pinch than the diodes, possibly the result of more electron passes through the converter. The current, voltage and impedance (all at the time of peak dose rate) are listed above the images, along with the total coupled energy and dose. The triode impedance is naturally lower than the diode impedance because it is two diodes connected in parallel.

In previous reflex diode experiments [2], simultaneous pulse-heating and plasma prefill increased the dose from thin (15 μm) converters from 75 rads to 150 rads, only 5% less than the maximum dose obtained using the triode configuration. These techniques are complicated to implement, but could provide similar improvement to the dose from the triode configuration.

It is desirable to balance the current division to the two cathodes by adjusting the inductances in the two paths, from the point where the posts connect to the ground plate to the cathode tips. This is done in practice by adjusting the length of the posts. Current monitors (dB/dt probes) were installed in three of the convolute posts to measure the current to the upstream cathode, and three dB/dt sensors were installed in the downstream cathode plate as shown in Fig. 4. The current monitors were calibrated using a test pulser, then re-calibrated in Gamble II using a short circuit load (AK gap = 0) for each diode individually. A triode shot with a short circuit load showed equal current division, implying equal inductances in the two cathode circuits.

Sample current waveforms are shown in Fig. 5 for the highest dose shot. The triode current (ITRIODE) matches the total current (IOUT) almost perfectly, although the upstream (IUS) and downstream (IDS) currents are somewhat different, especially after peak current. Attempts to equalize the current division by adjusting the AK gaps slightly were not very successful. Understanding and improving the current division is a subject for future investigation.

Sample ion current waveforms are compared with the total downstream current in Fig. 6 for three shots with different converters. The ion current is slightly greater for the 15-μm tantalum foil than for the 250-μm tantalum foil. The current is less and slightly later for the 13-μm
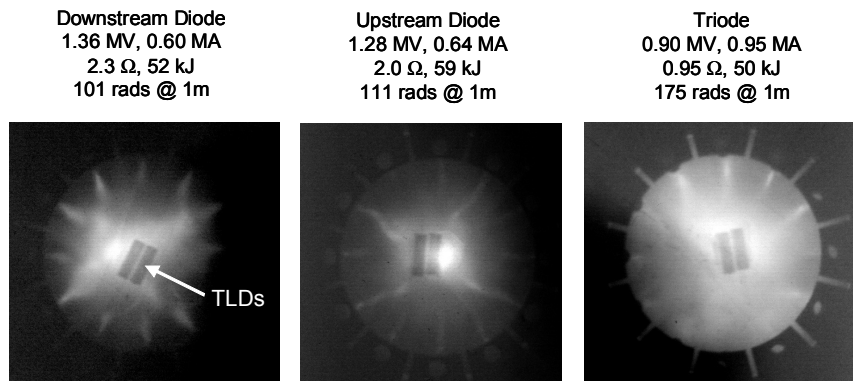
| Downstream Diode | Upstream Diode | Triode |
|---|---|---|
| 1.36 MV, 0.60 MA | 1.28 MV, 0.64 MA | 0.90 MV, 0.95 MA |
| 2.3 Ω, 52 kJ | 2.0 Ω, 59 kJ | 0.95 Ω, 50 kJ |
| 101 rads @ 1m | 111 rads @ 1m | 175 rads @ 1m |



**Figure 3.** X-ray pinhole images for shots with different diode configurations, all with 15-μm tantalum converters.
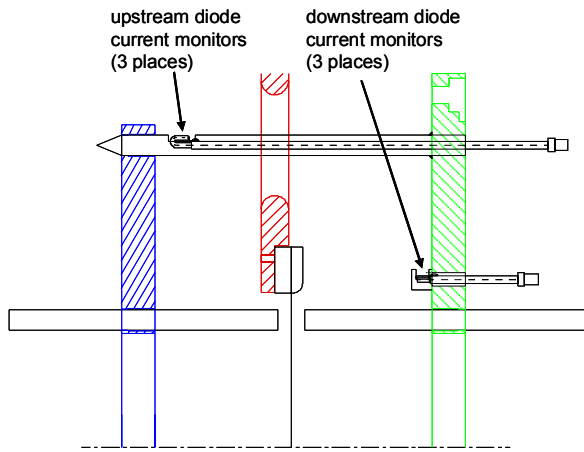
**Figure 4**. Current monitors to determine the current division between the two triode cathodes.

gold foil. For all three shots, the ion current signal begins at about 40-50 ns after the start of the downstream current, and reaches 100-200 kA, about 25-50% of the peak downstream current. Reducing the ion current (perhaps using the pulse-heating technique[4]) is a potential way to increase the x-ray dose by as much as 25%.

The step-wedge consists of seven thicknesses made from 1, 2, 3, 4, 6, 8 and 10 layers of 180-$\mu$m-thick aluminum strips. The step wedge is located 6.4 m from the diode, suspended above and parallel to a 10-cm thick tungsten "rolled edge" that casts a shadow on the image plate located 30 cm behind these objects. Image plate data in the shadow of the rolled edge serve as a background signal that is subtracted to account for indirect exposure of the image plate (via wall scattering, for example). The data behind the aluminum steps and in the fully-exposed regions above and below the steps are analyzed to calculate the transmission through the steps. This diagnostic reveals changes in the low-energy portion of the x-ray spectrum, since x-ray attenuation through thin aluminum is greatest for low-energy x-rays.
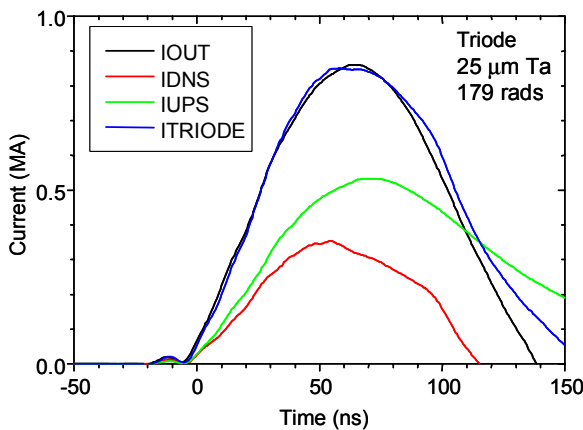


**Figure 5**. Triode current measurements: total current (IOUT), upstream cathode current (IUPS), downstream cathode current (IDNS) and total cathode current (ITRIODE = IUPS + IDNS).
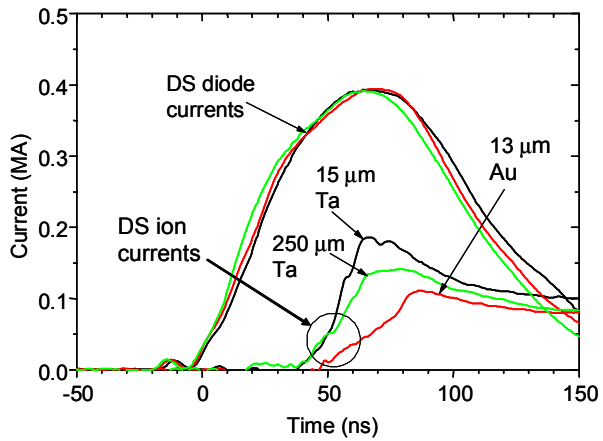


**Figure 6**. Ion currents and total currents measured for the downstream diode in the triode configuration, for different converters.

Transmission data for a large range (factor of 100) of converter thicknesses are shown in Fig. 7. The transmission through the thickest (1.8 mm) aluminum step varies from 69-88% as the converter thickness changes from 2.5 $\mu$m (Au) to 125 $\mu$m (Ta). Thinner converters transmit a greater fraction of the low-energy x-rays produced in the converter, and these photons are attenuated to a greater extent by the step wedge. (The transmission through 250 $\mu$m tantalum is less than for 125 $\mu$m; this is an anomaly that is not understood.) The data points for 2.5, 25 and 125 $\mu$m thicknesses are connected by dashed lines to show the data trend. Thick lines are derived from spectra described in the next section.

## III. COMPUTER MODELING

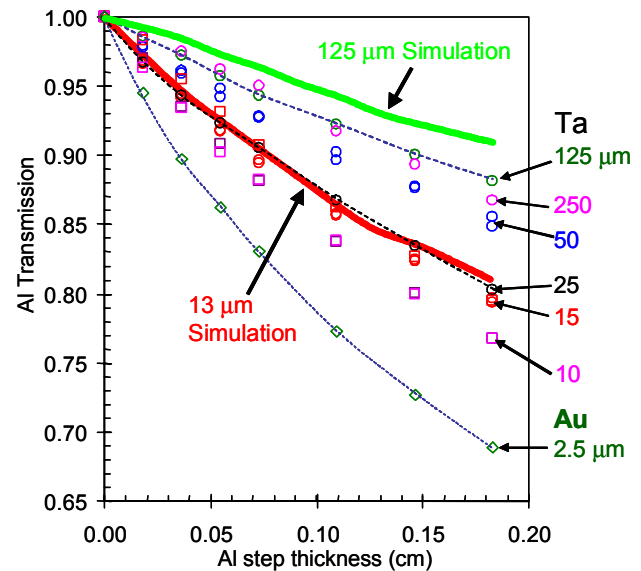The Gamble II reflex triode experiments were



**Figure 7**. Step wedge transmission data and comparison with simulations.

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simulated[5] using the particle-in-cell code LSP[6] and the Monte-Carlo electron-photon transport code ITS[7]. A Gamble II circuit model was used to drive the simulation and the triode configuration was approximated using axisymmetric conductors (no convolute). Proton emission was allowed from anode surfaces to provide an upper limit to the ion current. The simulations did not attempt to include electrode plasmas that, in experiments, close the AK gap and reduce the impedance.

The tantalum converter thickness was varied from 2.5 to 250 μm. Sample x-ray spectra from these simulations are shown in Fig. 8. "Number spectrum" is the spectrum of x-rays that escape from the tantalum in the forward 0-10° cone, with units of photons per steradian per electron per eV. The spectra have the same endpoint voltage (about 1.2 MV, about 20% higher than the experiments). The spectra for 13-, 50- and 250-μm converters are essentially identical for energies greater than 150 keV. For lower energies (excluding the K-line region, 60-80 keV), self-absorption in thicker tantalum reduces the amplitude of the spectra. The spectrum for the 2.5-μm converter has a reduced amplitude over the entire energy range, compared to the 13-μm converter. This indicates a reduction in the electron energy coupled to the converter, since otherwise, the transmission would be greatest for this thickness.

The computed spectral shapes are consistent with the step wedge data as indicated by the thick lines in Fig. 7. The calculated spectra indicate slightly higher transmission than the experimental points, possibly a result of the higher voltage in the simulations and impedance collapse and asymmetry in the experiments.

The simulations show that the reduced x-ray output for very-thin converters is a result of radial electron flow. A current flow pattern from a simulation is shown in Fig. 9. Current streamlines (or equivalently, contours of constant $rB_\phi$) are indicated by colors, from purple (lowest) to red (highest). Current flow from the cathode tips reaches the
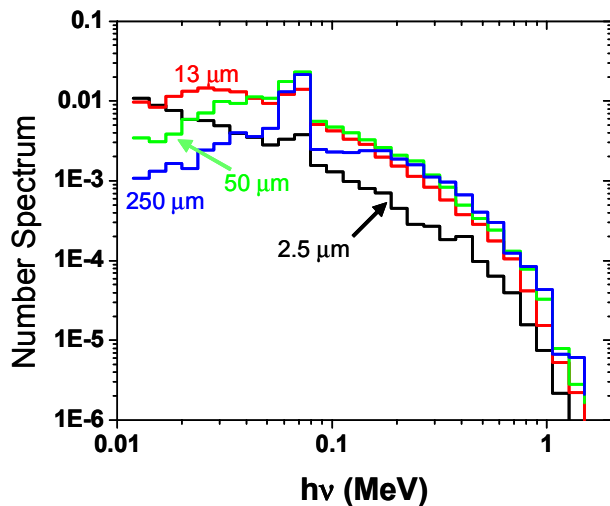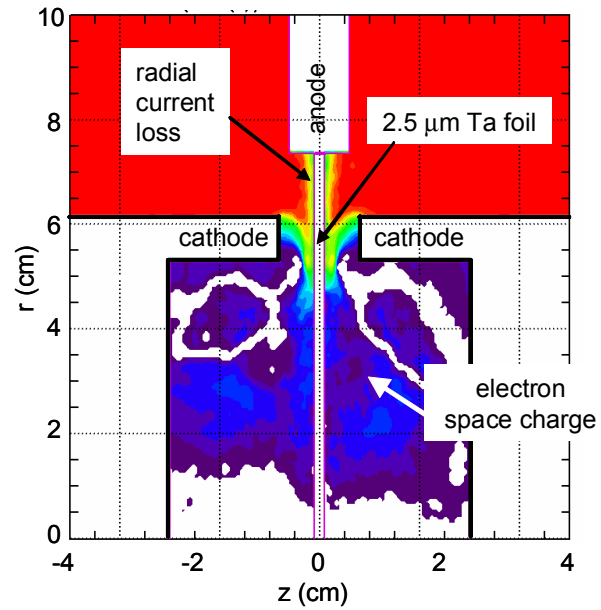


**Figure 9**. ITS calculation showing current contours (purple lowest, red highest) for a reflex triode with a 2.5-μm tantalum converter.

anode in a quarter-cyclotron orbit, characteristic of pinched-beam diodes operating at the "critical current." If this current were completely absorbed in the tantalum foil, the x-ray output would increase as the converter thickness decreases, because of decreased self-absorption. Instead, a significant fraction of the electrons propagate radially outward, parallel to the anode surface and are absorbed outside the x-ray target region. For the example in Fig. 9, the radial current loss is 30% of the total current. Of the remaining current, a significant fraction can be ions, so the fraction of the total current producing x-rays in the converter can become small, especially for thin foils.

The combined effect of these processes on the dose are summarized in Fig. 10, and compared with data from the experiment. Dose values (black circles) are calculated using the escape spectra, attenuated by the vacuum window and absorbed in TLD material for comparison with experimental values (red circles). The predicted and measured doses increase as the converter thickness decreases from 150 to 25 μm. For thinner converters, the dose decreases, with experiment and theory in reasonable agreement. The dose decrease is the result of current loss for thin converters, either by radial electron flow or by increased ion current. The simulations predict the ion current fraction increases from 35% with a 25 μm converter to 45% with a 2.5 μm converter, so the main reason for the 2.5-times dose decrease is probably the radial electron flow. The physics and scaling of this radial electron flow will be a subject of future research.

The simulation was repeated for a lower-impedance generator using the Gamble II circuit, but with 1-Ω generator impedance, and reducing the triode AK gaps by half. The peak voltage and current were 0.88 MV and 1.4
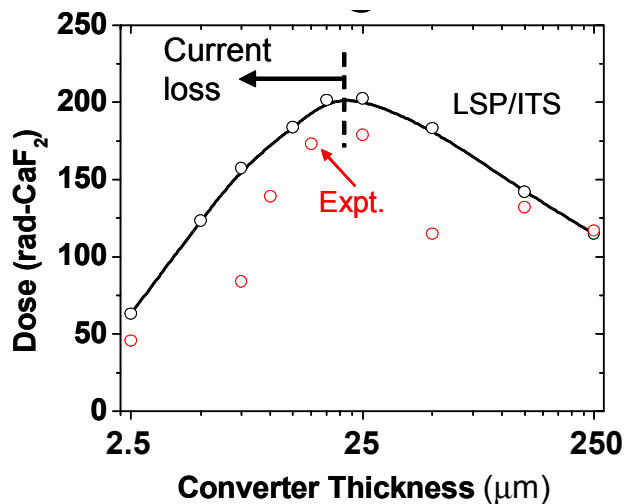


**Figure 8**. Spectra from LSP/ITS simulations of Gamble II reflex triode experiments with different tantalum converter thicknesses.

**Figure 10**. Dose dependence on converter thickness, experiment (red circles) and simulation (black circles).

MA, respectively. The optimum tantalum converter thickness for this case was 13 μm, two-times smaller than the optimum with the 2-Ω Gamble II circuit. The increased current may provide better radial confinement of the electrons, and the (slightly) decreased voltage reduces the CSDA range, so fewer passes through the converter are required to efficiently deposit energy. Either way, operating lower-impedance triodes driven by lower-impedance generators is an attractive way to enhance emission of x-rays in the 10-100 keV range.

## IV. SUMMARY

Gamble II experiments show reflex triodes are superior to diodes for coupling MeV electron beams to thin, high-atomic-number converters for efficient transmission of 10- to 100-keV x-rays. Enhanced emission of low-energy x-rays was verified in experiments using a step-wedge diagnostic. Computer simulations are in very good agreement with the experiments, and show why the optimum converter thickness is about 25 μm for the Gamble II triode parameters. For thinner converters, ion emission becomes a slightly greater fraction of the diode current, and, more important, electrons can flow parallel to the converter and connect to the anode at large radius, an effective current loss. The optimum converter thickness can be reduced for lower-impedance generators. Other options to be explored in the future include pulse-heating to reduce ion currents, plasma prefill to change the initial impedance time-history, and optimization of the vacuum window to reduce attenuation of low-energy x-rays.

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